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Performance analysis of a solar chimney power plant in the southwestern region of Algeria

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ABSTRACT

In this paper, we present the performance analysis of a solar chimney power plant expected to provide the remote villages located in Algerian southwestern region with electric power. Solar energy and the psychometric state of the air in the south of Algeria are important to encourage the full development of solar chimney power plant for the thermal and electrical production of energy for various uses. We are interested in Adrar where solar radiation is better than other areas of Algeria. The obtained results show that the solar chimney power plant can produce from 140 to 200 kW of electricity on a site like Adrar during the year, according to an estimate made on the monthly average of sunning. This production is sufficient for the needs of the isolated areas.

Contents

1. Introduction

Increasing of energy demand and large use of fossil fuels have generated great environmental concerns. Solar chimney power plant offers interesting opportunities to use pollution free resources of energy. It is a natural power generator that uses solar radiation to increase the internal energy of flowing air. The air mechanical energy can be transformed into electric power through suitable wind turbine. Solar chimney power plant concept was first investigated and published in the La energia electrica magazine, in 1903 by Isidoro Cabanyes [1]. In 1931, a description of a solar chimney power plant was presented by Günther [2]. Since then, many investigators applied for patents which were granted in Australia, Canada, Israel and USA [3]. The basic study on the solar chimney concept was performed by Schlaich's in the seventies of the twentieth century and in 1981, he began the construction of a pilot solar chimney power plant in Mansanares, Spain [3,4]. The chimney had a height of 195 m and a diameter of 10 m. The collection area (greenhouse) was 46,000 m^2. The maximum power output was up to 50 kW. Different materials such as single or double glazing or plastic were tested. Materials were chosen basically on the cost which

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Nomenclature

V	velocity (m/s)
A	area (m^2)
C_p	specific heat (J/kg K)
D	diameter (m)
e	height of the cover (m)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
I	solar radiation (W/m^2)
m	flow rate (kg/s)
G	global solar radiation (W/m^2)
P	power (W)
p	pressure (Pa)
Ra	Rayleigh number
t	time (s)
T	temperature (K)
H	height (m)
L	wall thickness (m)

Greek symbols

ε	emissivity
τ	transmitivity
ρ	density of air (kg/m^3)
η	efficiency
μ	viscosity of air (kg/m s)

Subscripts

abs	absorber
amb	ambient
coll	collector
r	radiation
c	convection
g	glass
f	fluid
o	outside
i	inside
tour	tower

should be the lowest. The device was an experimental setup where fundamental and experimental studies have been undertaken. Fundamental studies were carried out by Haaf et al. [3]. These authors have discussed energy balance, design criteria, cost of the system and energy production analysis. Experimental studies focused on the Mansanares prototype. Haaf [4] obtained few results from some preliminary tests on the Spanish systems. After the work done by Schlaich [5] and Schlaich et al. [6,7] in the solar chimney field, considerable efforts were made in analysing the performance of the chimney power plant in order to prove the feasibility as well as the profitability. These studies showed that the effectiveness of the solar chimney is strongly influenced by solar energy, although it remains practically constant with respect to the ambient temperature fluctuation. Pasumarthi and Sherif [8,9] have shown that solar chimney technology is a viable alternative technology adapted to hot climate areas such as of Florida. A mathematical model was developed by these authors to estimate the temperature and power output of solar chimneys. Bernardes et al. [10] conducted a theoretical analysis of a solar radial air heater, operating on natural laminar convection in steady state, to predict the thermo-hydrodynamic behaviour of the solar chimney device. Finite volume method in generalized coordinates was used to solve the governing equations. Velocity field and temperature distribution in the flow were obtained under imposed thermal conditions. Maia et al. [11] have presented a theoretical analysis of a turbulent flow inside a solar chimney. They showed that the most important physical elements in a solar chimney project are the tower dimensions as they cause the most significant variations in the flow behaviour. An increase in the height and in the diameter of the tower produces an increase in the mass flow rate and a decrease in the flow temperature. Pretorius et al. [12,13] developed a numerical model to simulate the performance of a solar chimney power plant. They demonstrated that greater power production is possible by optimizing the collector roof shape and height.

Studies on solar chimney were also related to drying process and ventilation. During the last decade, they focused on the optimization of the systems through the increase in the power production and the lowering of the installation cost [14,15]. In Southern Algeria, solar radiation is important throughout the year, large area is available, and the air psychometric state is convenient. These are favourable conditions for the development of solar chimney power plant. Chergui et al. [16] showed, in an earlier study, on solar chimney power plants in the south of Algeria, the importance of Adrar site as an interesting source of solar energy. In another study, Chergui [17] simulated a thermo-hydrodynamic behaviour analysis of the air flow through an axisymmetric system, such as chimneys, with defined boundary conditions. Chergui et al. [18] have also investigated the local characteristics of the fluid flow in the chimney. In their study, the velocity field and the temperature distribution through the system were determined through the resolution of a mathematical model representing the flow conservative equations, using the finite volume method under certain assumptions. The effect of fluid flow regime on the performance analysis of solar chimney power plants was performed by Chergui et al. [19] through the influence of the Rayleigh number on the generated power. Chergui et al. [20] have shown that the obtained results as well as the velocity field are in a good agreement with experimental data gotten at the Manzanares power plant.

This study presents an analysis about the influence of some geometrical and physical parameters, such chimneys height and solar radiation, on the power output of a solar chimney power plant constructed at Adrar site and dimensioned for some MW power.

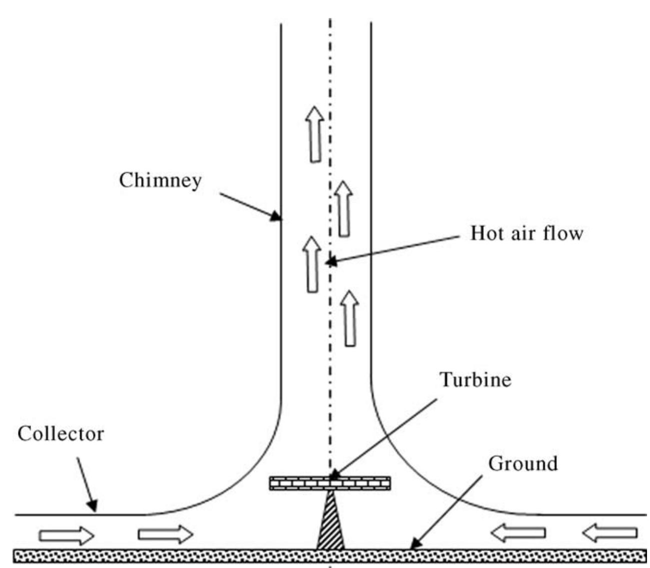

Fig. 1. Solar chimney power plant schematic representation.

2. Mathematical model and boundary conditions

2.1. Physical model

A typical solar chimney power plant is composed of a solar collector whose function is to increase the energy level of the air by greenhouse effect of a chimney tower to ensure the circulation of air per gradient of density. The typical solar chimney is composed also of an aero generator to produce electric power (see Fig. 1).

The performance analysis of the chimney power plant is based on a mathematical model developed by Schlaich et al. [6,7]. This mathematical modeling is based on momentum and energy balance equations, in the collector and in the chimney as well.

2.2. Energy balance in the collector

The collector has a circular form. The balance equation applied to a control volume, with an annular form, gives the differential equation of the temperature distributions, T_f, in the collector:

$$\frac{dT_f}{dr} = \frac{2\pi r}{\dot{m} c_p}\left(\tau_{in} e_{abs} I_t - \tau_{ext} e_{abs} \sigma (T_{abs}^4 - T_{amb}^4) - h(T_f - T_{gi}) + \frac{k_{soil}}{L_{soil}}(T_{abs} - T_{soil})\right) \tag{1}$$

Three other balance equations are added to Eq. (1). The first one, is on the surface of the soil (2), the second on the inside face of the cover (3) and the third one, is on the external face of the cover (4).

$$\tau_{in} e_{abs} G = \tau_{ext} e_{abs} \sigma (T_{abs}^4 - T_{amb}^4) - h_{abs}(T_{abs} - T_f) + \frac{k_{soil}}{L_{soil}}(T_{abs} - T_{soil}) \tag{2}$$

$$h_{gi}(T_f - T_{gi}) = \frac{k_g}{L_g}(T_{gi} - T_{go}) \tag{3}$$

$$\frac{k_g}{L_g}(T_{gi} - T_{go}) = h_{go}(T_{go} - T_{amb}) \tag{4}$$

The effect of the wind and the ambient air, on the front or the back face of the collector, on heat transfer [21], is given by the following equation:

$$h_w = 5.67 + 3.86 V_w \tag{5}$$

where V_w, is the velocity of the wind.

The convective heat exchange between the cover and the fluid flow, and between the fluid flow and the absorber, given respectively by the coefficient, $h_{c,f\text{-}g}$ and $h_{c,f\text{-}abs}$ are considered as equal [21]

$$h_{c,f\text{-}g} = h_{c,f\text{-}abs} = \frac{k_f}{D_H} \tag{6}$$

where D_H, is the hydraulic diameter.

The collector has a circular shape, with radius, R, and height, e. The hydraulic diameter is then

$$D_H = \frac{4(2\pi R \times e)}{2(2\pi R + e)} \tag{7}$$

For the solar chimney power plant case, $e \ll R$, the expression given by (7), can be simplified to

$$D_H \approx 2e \tag{8}$$

The Nusselt number, Nu, is calculated according to the correlations of Churchill and Chu, given by [21]

$$Nu = 0.54 Ra^{0.25}, \quad \text{for}: 2.10^4 < Ra < 8.10^7 \tag{9}$$

$$Nu = 0.15 Ra^{0.33}, \quad \text{for}: 8.10^7 < Ra < 8.10^{11} \tag{10}$$

The radiative heat transfer coefficient between the cover and the sky is

$$h_{r,g-s} = \frac{1}{2}\sigma \varepsilon_g (1 - \cos\beta)(T_g + T_{sky})(T_g^2 + T_{sky}^2) \tag{11}$$

where T_g, is the temperature of the cover, and T_{sky} the equivalent temperature of the sky, given by

$$T_{sky} = 0.0552 T_{amb}^{1.5} \tag{12}$$

The radiative heat transfer coefficient between the cover and the absorber is

$$h_{r,g\text{-}abs} = \frac{\sigma (T_g + T_{abs})(T_g^2 + T_{abs}^2)}{(1/\varepsilon_{abs}) + (1/\varepsilon_g) - 1} \tag{13}$$

where T_{abs}, is the absorber temperature, and ε_{abs} its emissivity.

2.3. Momentum balance in the chimney

The chimney is considered as a pipe tower of pressure with weak loss in friction because of its optimal ratio between the surface and the volume. The efficiency of the chimney power plant, the conversion of heat flow into kinetic energy, are practically independent from the high temperature of the air temperature in the collector. By applying the momentum balance equation on a control volume in the tower, we can deduce the expression of the maximum air velocity in this tower. It is given by

$$w_{\max} = \sqrt{2gH_{tour}\frac{\Delta T}{T_{amb}}} \tag{14}$$

where H_{tour}, is the tower height. We must underline that the square velocity is proportional to the difference of the temperature and to the tower height. The flow power is expressed by

$$P_{tot} = \eta_{tour} P_u = \left(\frac{gH_{tour}}{T_{amb}}\Delta T \rho_{coll}\right) V_{inlet\,tour} A_{tour} \tag{15}$$

The pressure head between the inlet of the tower and its outlet is calculated by

$$\Delta p_{tot} = \rho_{coll} g H_{tour} \frac{\Delta T}{T_{amb}} \tag{16}$$

The electric power delivered by the device is then

$$P_{elec} = \frac{2}{3}\left(\eta \frac{gH_{tour}}{c_p T_{amb}}\right) A_{coll} I_t \tag{17}$$

For a given chimney power plant, geometrical data (height and diameter of the tower, diameter of the collector, distance between the soil and the cover), for specified thermal conditions (such as ambient air temperature, solar radiation), we can deduce easily the evolution of the chimney power during the year by using a developed computer software based on the numerical solution [22–25] of the previous Eqs. (1) to (17).

3. Results and discussion

3.1. Performances analysis example of the chimney power plant

This analysis is based on the mathematical model developed in above sections. Some parameters used in the performance system analysis are given in Table 1.

Fig. 2 shows the effect of chimney height and collector diameter on the generated power. The ambient temperature and the solar irradiance effect on the power production of the installation are given by Fig. 3. It is noted that the power production increases with the increase in the radiation and the ambient temperature.

Table 1
Technical data used in the solar chimney power plant.

Parameters	Value	Parameters	Value
Chimney height (H_{tour})	200 m	Product of transmittance and absorbance of the collector ($\tau\alpha$)	0.65
Chimney diameter (D_{tour})	10 m	Solar radiation (G)	800 W/m^2
Collector diameter (D_{coll})	500 m	Ambient temperature	30 °C
Distance from ground to the cover (H_{coll})	2.5 m	Turbine efficiency (η_t)	0.8

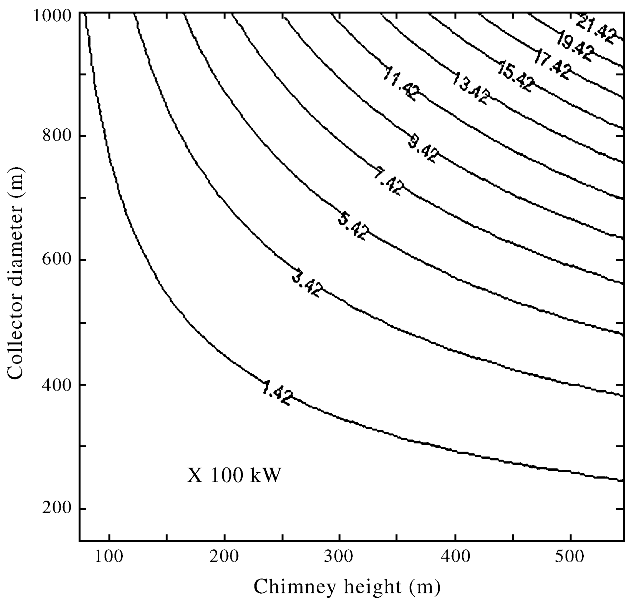

Fig. 2. Effect of chimney height and collector diameter on the generated power.

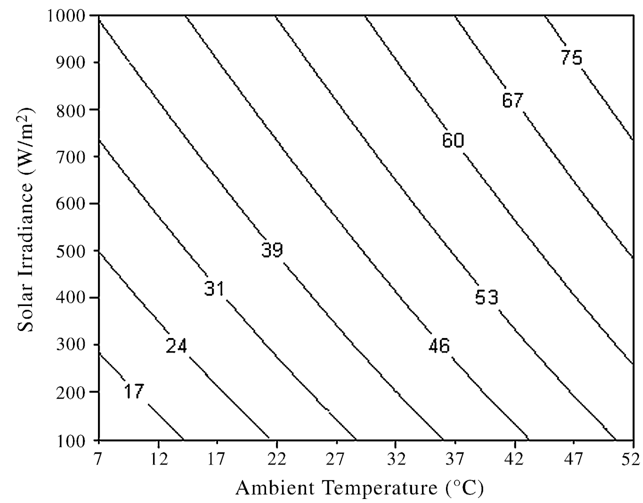

Fig. 4. Effect of ambient temperature and solar irradiance on the collector exit air temperature in (°C).

However, the solar irradiance, is the dominating factor over the assignment of solar chimney power plant electricity production, compared to the ambient temperature. Another analysis was carried out takes into account the collector diameter variations and tower size.

Fig. 2 indicates that the size of the collector and the tower are depending on the power produced by the solar chimney power plant. The power obtained increases in a non-linear way with the increase of the collector diameter and the tower height. It increases quickly when the collector and the tower sizes are small, but it increases slowly when the sizes are significant.

Nearly 342 kW of electricity can be produced by a power plant having a collector diameter of 600 m and a tower height of 250 m.

Figs. 4 and 5 show, respectively, the effect of the ambient temperature and the solar irradiance on the air temperature at the outlet side of the collector and on the ground temperature. We note that this temperature increase with the solar irradiance and the ambient temperature.

Fig. 6 shows the air temperature variation crossing the collector versus the collector radius under 800 W/m^2 as radiation and 30 °C as ambient temperature.

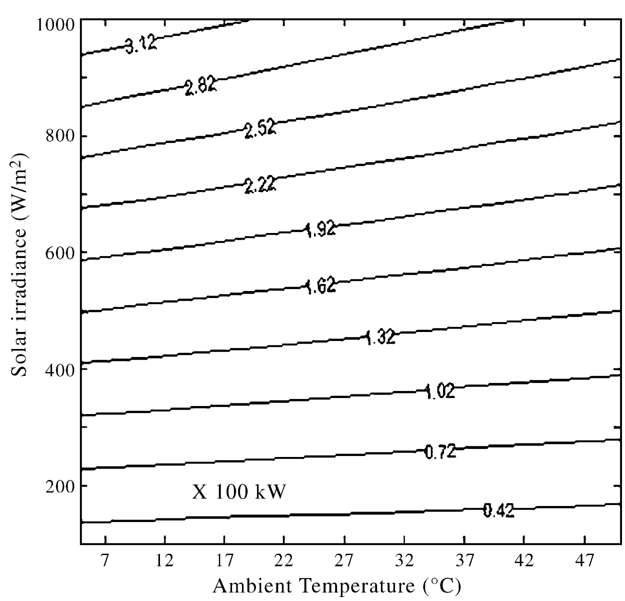

Fig. 3. Effect of ambient temperature and solar irradiance on the generated power.

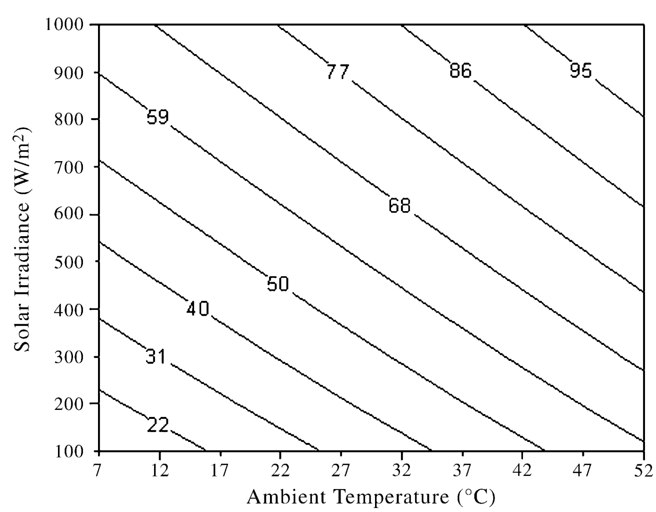

Fig. 5. Effect of ambient temperature and solar irradiance on the ground temperature in (°C).

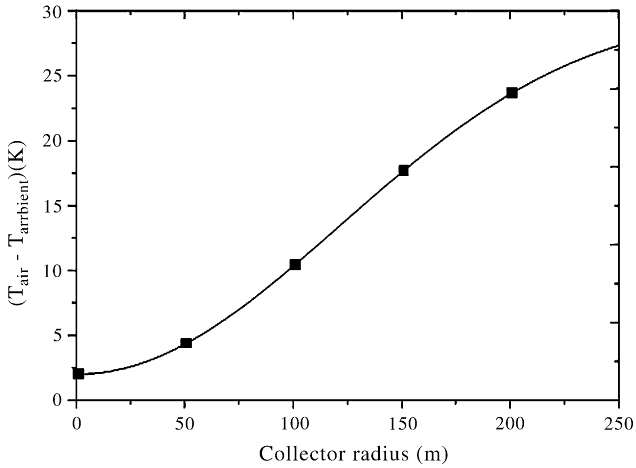

Fig. 6. Air temperature distributions through the collector.

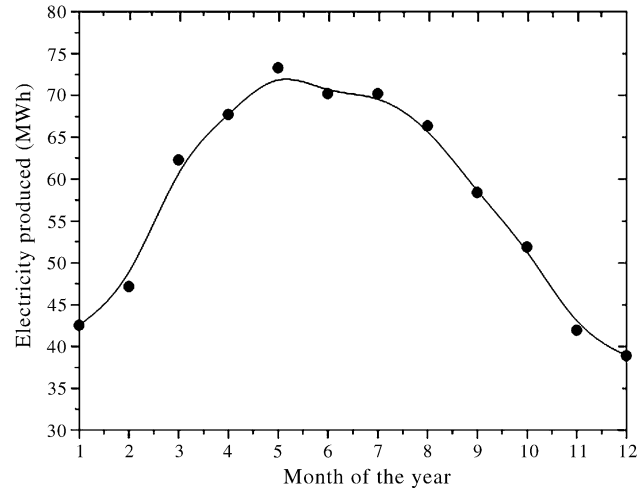

Fig. 9. Monthly average electricity produced in MWh.

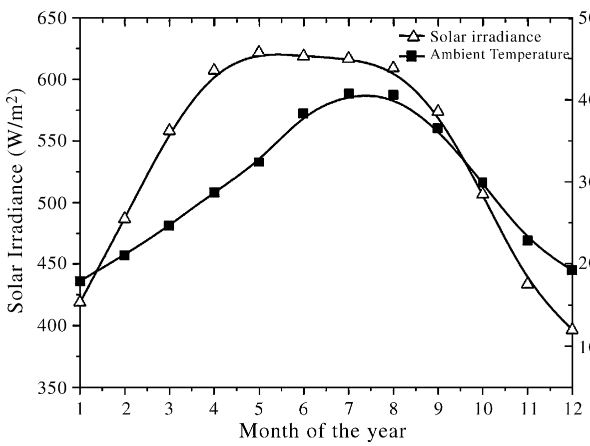

Fig. 7. Monthly average solar irradiance and ambient temperature.

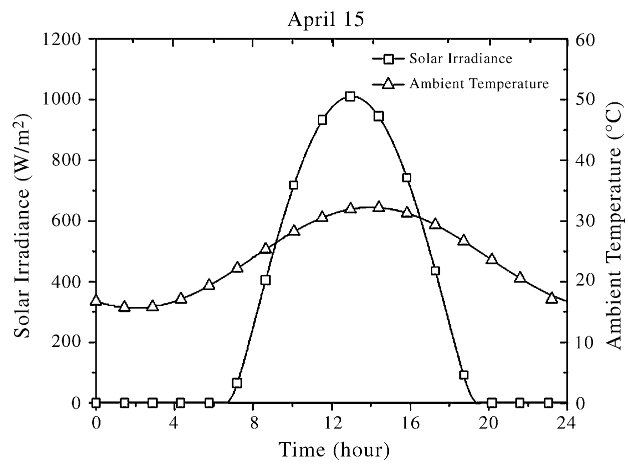

Fig. 10. Variation of solar irradiance and ambient temperature versus time for April month.

3.2. Application to Adrar site—Algerian southwestern region

We present in this work an analysis of a possible solar chimney power plant implantation in the Adrar site, by giving importance to the power generated during the year and especially during the period of maximum loading by a solar chimney power plant, in which the height and the diameter of the chimney are 200 m and 10 m, respectively, and the diameter of the solar collector is 500 m. The two parameters of analysis are the solar irradiance and the ambient temperature.

Adrar is located at the south-western region of Algeria where the solar layer is important. In his study, Capderou [26] has shown that the annual energy of the solar radiation is approximately 2.2 MWh/m^2/an and the photoperiod reaches 11 h per day for all

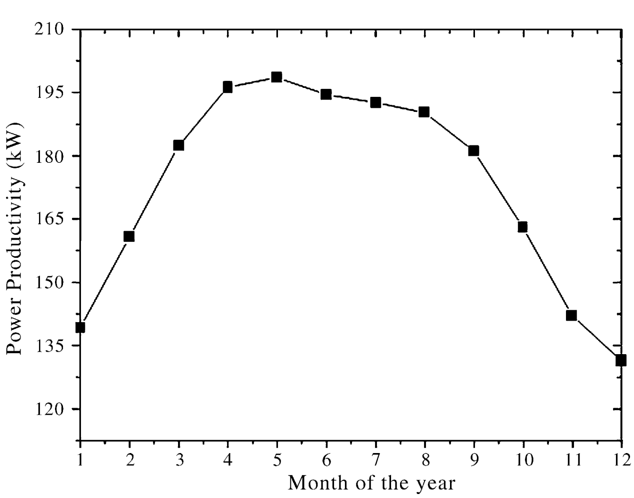

Fig. 8. Monthly average solar chimney power productivity.

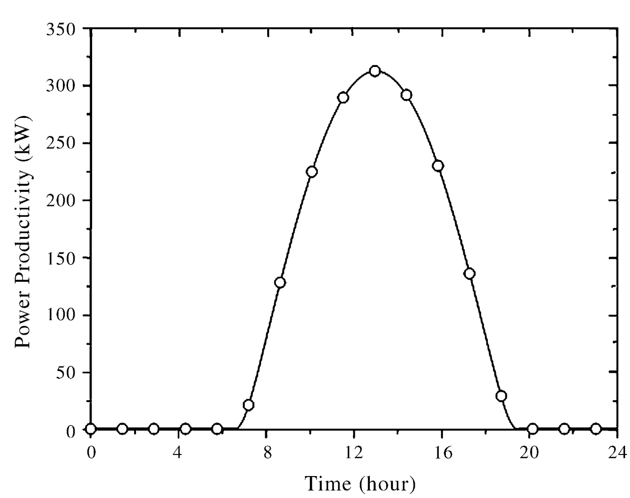

Fig. 11. Variation of power productivity versus time for April month.

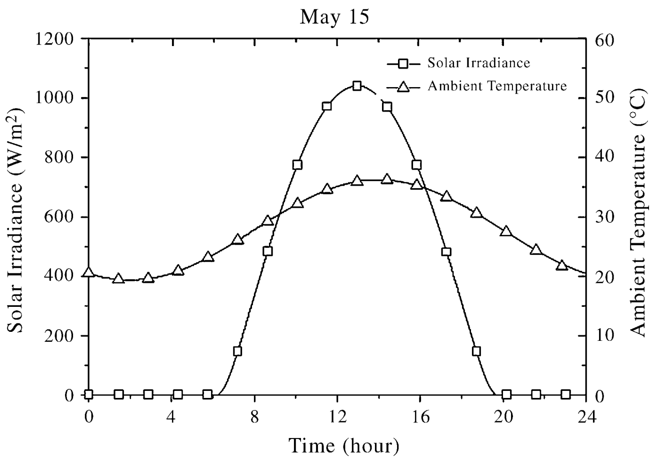

Fig. 12. Variation of solar irradiance and ambient temperature versus time for May month.

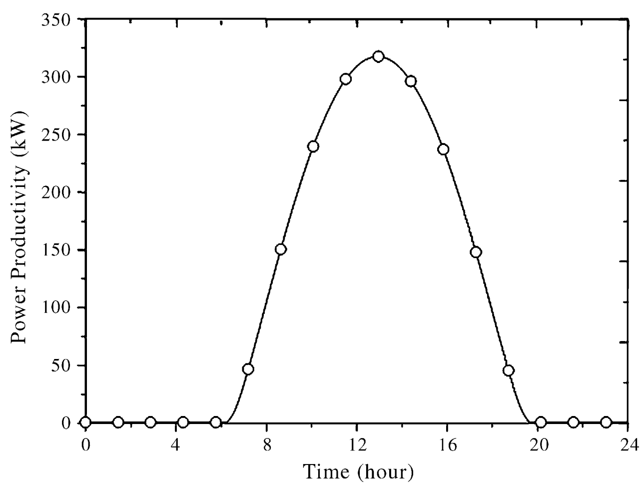

Fig. 13. Variation of power productivity versus time for May month.

the year, and the maximum is reached between 12 and 13 h. The results of this analysis show that the production of power by the solar chimney power plant is worthy to be studied in this area.

Fig. 7 shows the monthly average variation of solar irradiance and ambient temperature in Adrar. Fig. 8 demonstrates the evolution of power production versus the time course. The output of electricity range is between 140 and 200 kW during all the year.

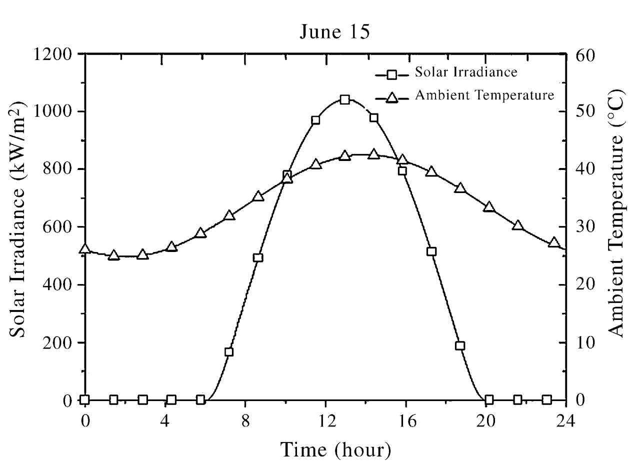

Fig. 14. Variation of solar irradiance and ambient temperature versus time for June month.

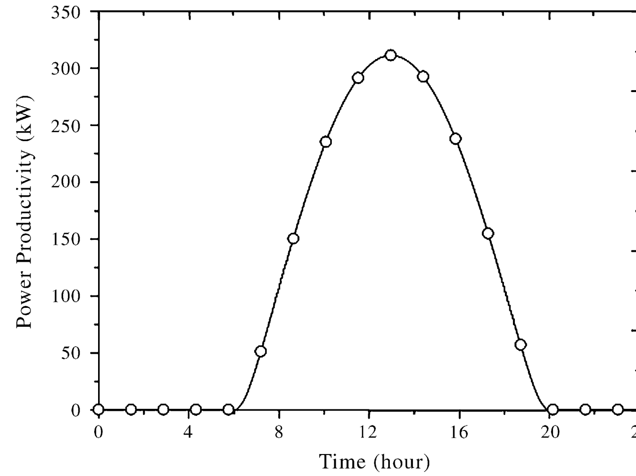

Fig. 15. Variation of power productivity versus time for June month.

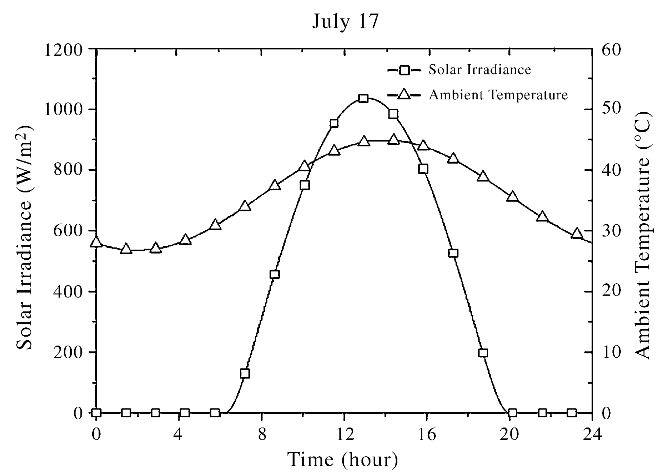

Fig. 16. Variation of solar irradiance and ambient temperature versus time for July month.

The Solar chimney power plant can produce more from March to September, because the solar irradiance is high in this period. Moreover, we do not forget in Figs. 7 and 8 that the variations of the solar irradiance and the power production have the same behaviour.

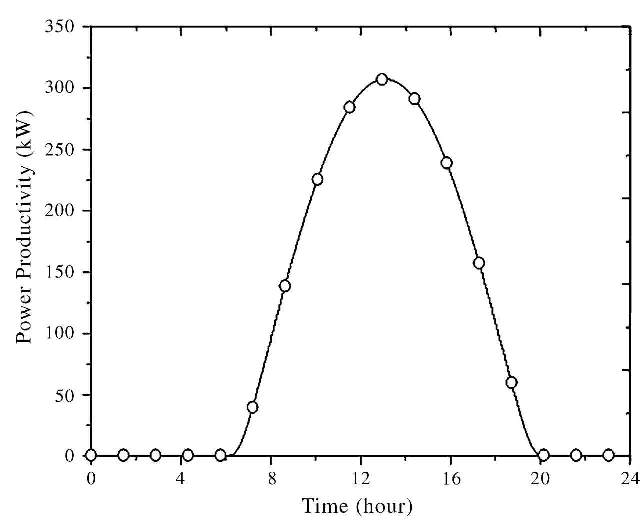

Fig. 17. Variation of power productivity versus time for July month.

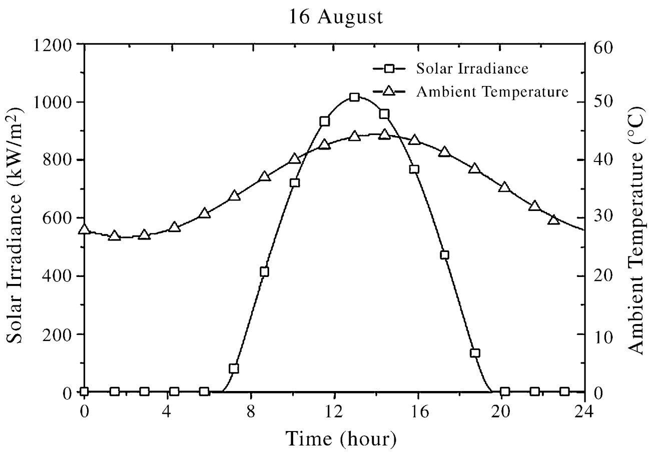

Fig. 18. Variation of solar irradiance and ambient temperature versus time for August month.

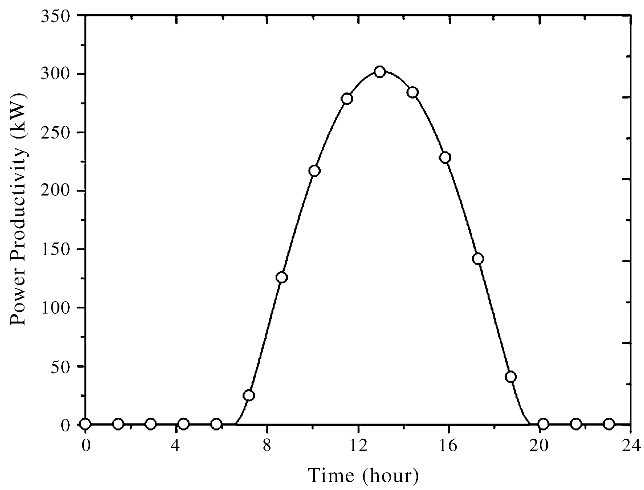

Fig. 19. Variation of power productivity versus time for August month.

The average monthly solar irradiance variation is different from that of temperature. In June, Adrar possess a good quality of solar irradiance with approximately 620 W/m^2 and the minimum of irradiance in December with approximately 380 W/m^2. Fig. 9 shows the production of energy where the output of electricity ranges is between 38 and 72 MWh during all the year.

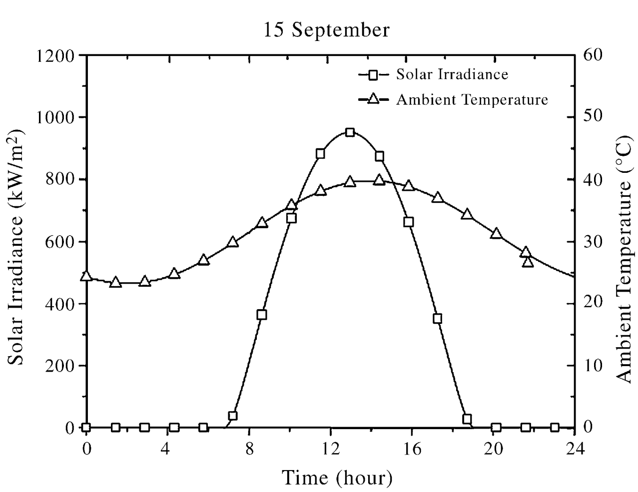

Fig. 20. Variation of solar irradiance and ambient temperature versus time for September month.

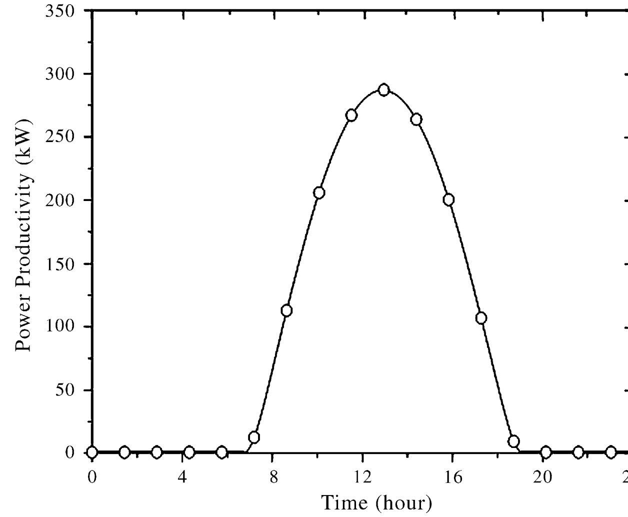

Fig. 21. Variation of power productivity versus time for September month.

3.3. Evaluation of the power generated by a solar chimney power plant during the months of maximum loading in Adrar site

Both Figs. 10–21 enable us to take into consideration the monthly average variations of the solar irradiance and the ambient temperature in Adrar during the hottest months, and for the loaded electric power request i.e.: between April and September. It is to be noticed that the minimal monthly average temperature which occurs on April is equal approximately to 30 °C while the maximum monthly average temperature, which occurs on July attains 41 °C. The variation of the solar irradiance is different. Adrar has the best solar irradiance on June with approximately 625 W/m^2 and the minimum of irradiance occurs on September with approximately 575 W/m^2.

These figures and Fig. 8 show that the output of average power productivity ranges are between 180 to 200 kW in this hottest period of the year.

4. Conclusion

The work presented in this study is related to the performance analysis of a solar chimney power plant expected to provide the remote villages located in Algerian southwestern region with electric power. The obtained results show:

1. The generated power depends on the solar irradiance, the ambient temperature, the height of the tower and the surface of the collector.
2. The efficiency both of the collector and the turbine has a significant role in the improvement of the system performances.
3. For a given climatic conditions, the produced power increases with the increase of the tower height and the collector surface. This production is more influenced by the solar irradiance than by ambient temperature.
4. The solar chimney power plant can produce from 140 to 200 kW of electricity, on a site like that of Adrar, and that lasts all the year, according to an estimate made on the monthly average of sunning. This production is sufficient to satisfy the needs of the isolated areas, and the solar heat collector of the device could also be used as a greenhouse for agricultural uses.

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